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THE BIFURCATION BEHAVIOUR OF VERTICALLY IRREGULAR BUILDINGS IN LOW SEISMICITY REGIONS

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SUMMARY

Recent investigations by the authors have shown that existing displacement predictive procedures (including push-over analysis) could grossly underestimate the inelastic storey-drift of a multi-storey building under ultimate conditions if the collapse mechanism bifurcates from one principal displacement shape into two principal displacement shapes following the formation of certain plastic hinges. Such bifurcation behaviour has been demonstrated in buildings which have not been designed to fail in a ductile mechanism This behaviour is further studied in this paper with the analyses of a number of two-degree-of-freedom models (comprising a "lower" lumped mass and an "upper" lumped mass). A plastic hinge is assumed to form above the lower lumped mass. It has been found that the displacement of the lower lumped mass decreases while the strength reduction factor (defining the yield strength of the plastic hinge) increases. An important feature of the developing procedure of storey drift prediction is the use of the "floor" displacement response spectrum (derived in accordance with the motion of the lower lumped mass) to predict the inelastic drift behaviour of the upper lumped mass.

INTRODUCTION

Vertical irregularities in a multi-storey building such as the presence of a "soft-storey" or sudden change in geometry and stiffness (Figure 1) have been recognised widely as undesirable features of a building from an earthquake resistant viewpoint [Paulay & Priestley, 1992]. However, such irregularities are commonly found in buildings in regions of low and moderate seismicity where earthquake resistant considerations are seldom considered in the schematic design of the building. Earthquake loading standards [AS1170.4,1993] generally give provisions for the design of such irregular structures based on dynamic analyses, including elastic modal analyses. However, the conventional elastic analysis procedures have the shortcomings of not realistically representing the dynamic behaviour of an inelastically responding structure.

Inelastic storey-drift is an important parameter in the seismic performance evaluation of a building at the ultimate limit state since the parameter is directly related to:

(i) Maximum strains developed in the plastic hinges.

(ii) Damages to attached non-structural components.

" P-Δ" effects.

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A number of methods that have been developed to predict inelastic storey-drifts are listed as follows:

1. Time-History Analysis Method
2. Effective Height Method [Priestley, 1995]
3. Generalised SDOF System Method [Calvi & Pavese1995; Chen, Lam & Mendis, 1998]

The inelastic time-history analysis (THA) method is capable of mo,delling inelastic storey drift behaviour including bifurcation behaviour, provided that the finite element model of the structure represents realistically the cyclic inelastic deformation behaviour of the structure. However, THA is not commonly used in practice due to its high running costs and the requirements for a sufficient number of representative accelerograms. In this study, THA has been used to illustrate and quantify the effects of bifurcation behaviour.

The effective height method is simple but is restricted to regular building structures. This method is only applicable to buildings developing one of the classical collapse mechanisms. Thus, there is no allowance for bifurcation behaviour in the procedure.

The generalised single-degree-of-freedom (SDOF) system method draws the analogy between the displacement of a SDOF system and that of a multi-degree-of-freedom (MDOF) system based on an assumed displacement shape. It is considered that such procedures would take into account the post-elastic behaviour of the building provided the assumed displacement shape of the building has been realistically represented. Push-over analyses [Lawson, Vance & Krawinkler, 1994] have been used to determine inelastic displacement shapes which are affected significantly by plastic hinge formation [Chen, Lam & Mendis 1998]. This method gives more realistic predictions than the elastic modal analysis method, as the inelastic displacement shape of the building has been approximated by push-over analysis. However, this method is incapable of modelling the dynamic bifurcation response behaviour which is described later in the paper. Significantly, it has been found from recent investigations by the authors that such procedures could grossly under-predict storey-drifts if the collapse mechanism of the building bifurcates from one principal elastic displacement shape into two principal displacement shapes following the formation of certain plastic hinges (Figure 2a). Consequently, existing displacement predictive procedures based on the SDOF analogy has major limitations when applied to building structures which have not been designed to develop a well defined collapse mechanism under ultimate conditions.

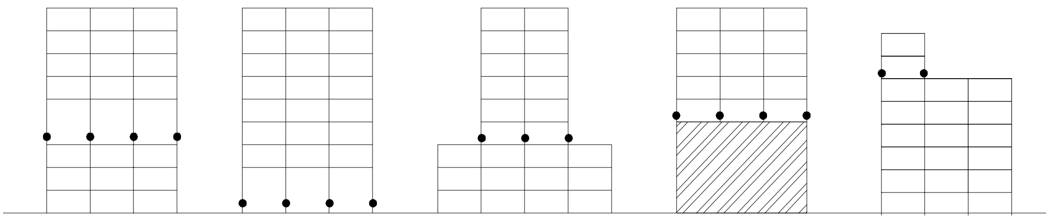

Figure 1. Vertically irregular buildings and locations of the weak storey.

It has been found that significant yielding at a weak storey in the upper level of a multi-storey building structure can cause bifurcation to occur (Figure 1), [Chen, Lam & Mendis 1998, 1999]. Dynamic coupling actions between the two parts of the building (separated by the weak storey) can be very complex. Thus, a two-degree-of-freedom model has been used at this stage of the research to highlight the major trends of bifurcation.

In this paper, bifurcation behaviour is studied based on the analyses of a number of two-degree-of-freedom lumped mass models. Significantly, a plastic hinge can form at the base of the upper lumped mass causing bifurcation to occur (Figure 2b).

The study comprises the following components:

1) The prediction of the motion of the lower lumped mass [section 2].
2) The prediction of the inelastic drift of the upper lumped mass based on the predicted motion of the lower lumped mass [section 3].

The earthquake records of Elcentro and Parkfield were employed in this study, their details are listed in Table 1.

Table 1. Earthquake accelerograms used in this paper.

Accelerogram	Location of rupture	Date of rupture	Magnitude	Distance (km)	PGA(g)
Elcentro	Elcentro	18/05/1940	6.6	8	0.37
Parkfield	Parkfield	28/06/1966	5.6	7	0.51

Program Ruaumoko [Carr, 1998] was used in the computer analyses.

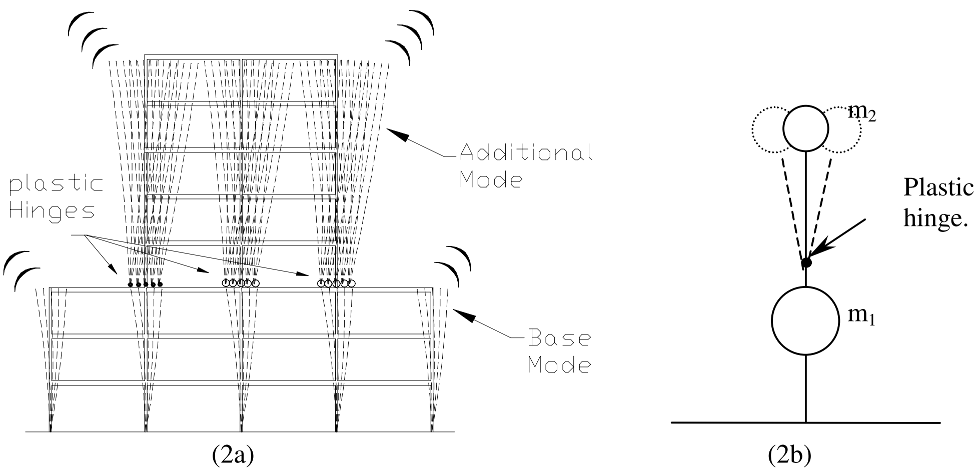

Figure 2. Illustrated bifurcation behaviours, and two-degree-of-freedom model.

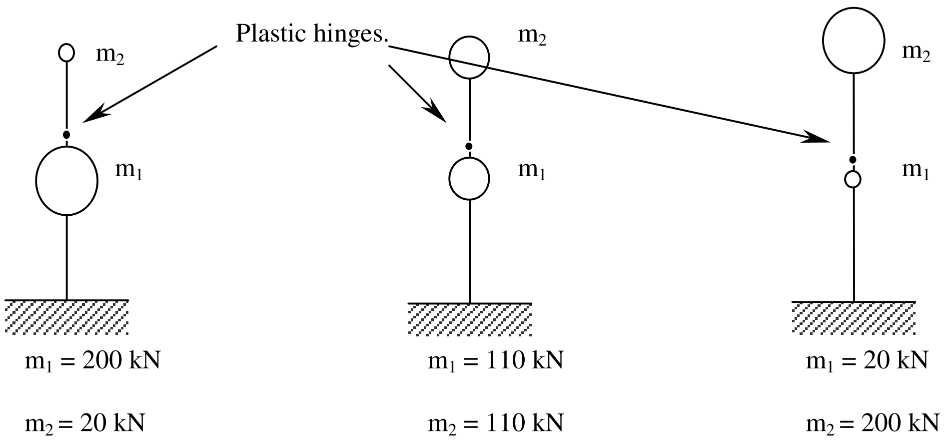

Figure 3, Two-degree-of-freedom models used.

2. THE PREDICTION OF THE MOTION OF THE LOWER LUMPED MASS

A number of 2DOF models with different relative mass and different plastic hinge reduction factor R (R=1, 0.33, 4, 6, 8) have been analysed (Figure 3).

It is shown in Figure 4 that the maximum displacement of the lower lumped mass generally decrease with increasing R factors. Thus, it is conservative to predict the motion of the lower lumped mass based on elastic modal analyses. Further research employing more extensive analyses will be undertaken to quantify the reduction of motion due to the plastic hinge formation.

The frequency content of the motion of the lower lumped mass has also been studied. It was found that the dominate period of motion is generally insensitive to ductile yielding of the plastic hinge formed above the lower lumped mass. However, some small increase in the dominant period with increasing R factor has been observed. The frequency content can be defined by a “floor” displacement response spectrum as shown in Figure 5. The “floor” displacement response spectrum is in analogy with the “ground” displacement response spectrum which defines the frequency content of the motion at ground level.

THE PREDICTION OF THE INELASTIC DRIFT OF THE UPPER LUMPED MASS

It has been proposed that the inelastic displacement behaviour of single degree of freedom system can be approximated by a elastic substitute structure in which the effects of stiffness and strength deterioration and energy absorption resulted from ductile yielding can emulated by adjusting the stiffness and viscous damping of the equivalent elastic substitute structure [Shibata & Sozen 1976]. In the context of the two-degree-of-freedom models, the inelastic drift behaviour of the upper lumped mass can be approximated by an elastic displacement response spectrum.

The concept of the substitute structure is employed to predict the inelastic drift behaviour of the upper lumped mass using the “floor” displacement response spectrum which has been developed in accordance with the predicted motion of the lower lumped mass [refer section 2].

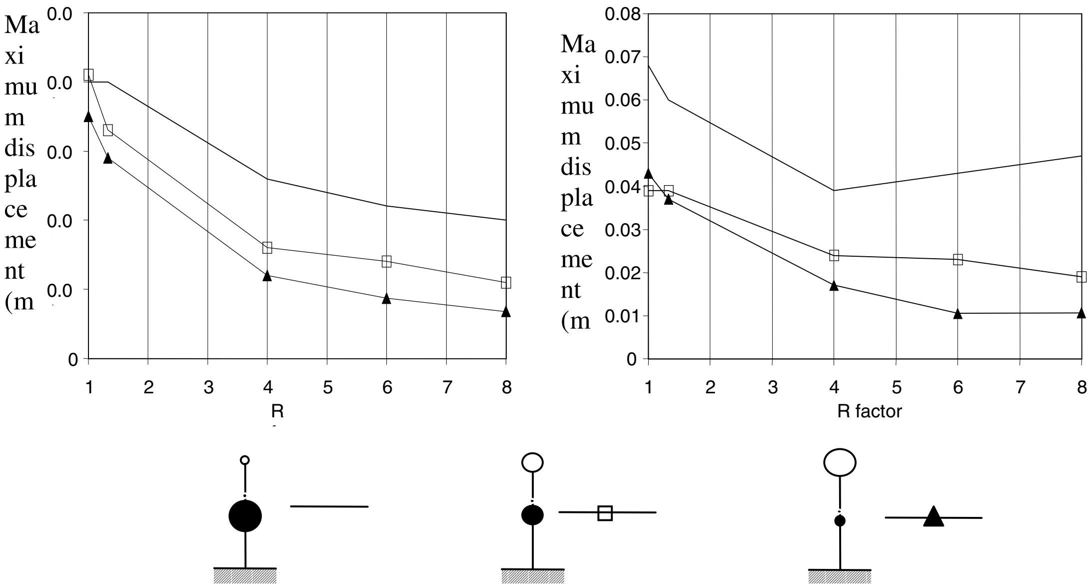

Figure 4, The maximum displacements of the lower lumped mass decrease with increasing R factor of the plastic

The following is a list of observations of the "floor" displacement response spectrum developed in this study from the analyses of the 2DOF models (Figure 5).

- The shapes of the “floor” displacement response spectra are generally affected by the formation of the plastic hinge.
- Such effects become significant when the upper lumped mass is relatively larger.
- The response spectrum level decreases with increasing R factor.
- The dominant periods of the floor displacement response spectra (representing the natural period of the floor motion) increases slightly following plastic hinge formation.

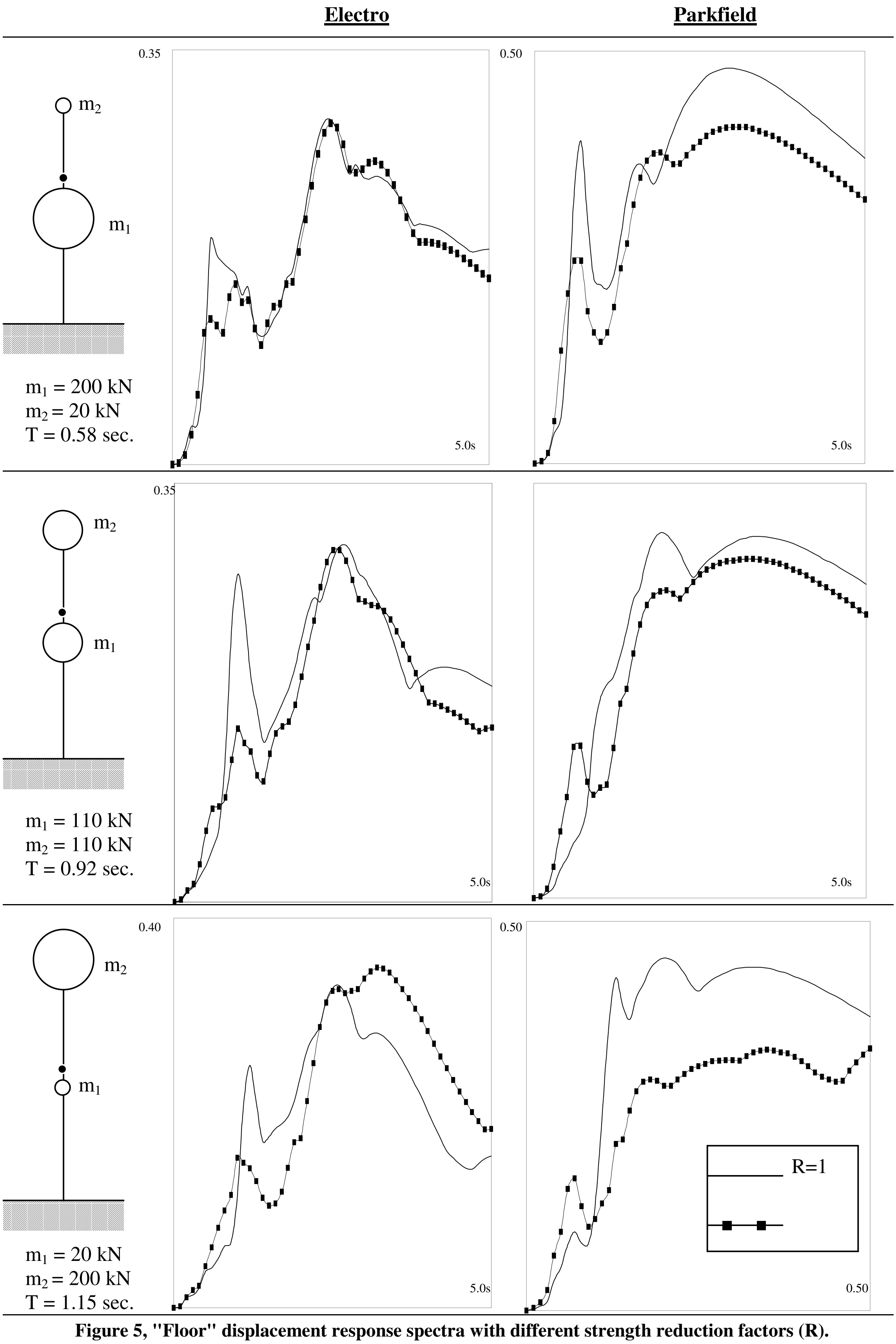

Figure 5, "Floor" displacement response spectra with different strength reduction factors (R).

CONCEPTION OF A SIMPLIFIED INELASTIC STOREY DRIFT PREDICTIVE PRECEDURE

A simplified predictive procedure has been conceived based on the considerations described in Section 2 and 3. The procedure comprises the following steps:

Step 1: Determination of the maximum displacement at the base of the “weak storey”(the lower lumped mass).

The relative elastic displacement at the base of the weak storey can be obtained by elastic modal analysis. Alternatively, the effective height procedure proposed by [Priestley 1995] can be used to assist in the prediction.

Strictly speaking, the total floor displacement (at the base of the weak storey) is the sum of the relative displacement and the ground displacement at any particular instance. However, the ground displacement can be ignored in situations where the floor displacement is very much larger than the peak ground displacement (eg. plastic hinge occurring at the upper level of a very tall building).

It has been shown in Figure 4 that this displacement can be reduced to account for the effect of ductile yielding at the upper floors. Thus, there are scopes in refining the prediction described above.

This response spectral displacement at infinite periods in floor displacement response spectrum is the "maximum floor displacement" (In analogy with the "maximum ground displacement" in a ground displacement response spectrum.).

Step 2: Determination of the Dominant Period.

An initial prediction of the dominant period can be obtained from elastic modal analysis. However, adjustment can be made to account for the small period shift resulted from ductile yielding (Figure 5).

Step 3: Determination of the “floor” displacement response spectrum of the upper floor (at the base of weak storey).

The dominate period and the maximum displacement have been identified as the two most important parameters defining the floor displacement response spectrum. The dominant period has been determined in Step 2. The maximum spectral displacement can be derived based on amplification of the “maximum floor displacement” which has been determined in Step 1. The quantity of the amplification is the subject of further research.

Having determined the dominant period, maximum floor displacement, the maximum floor response spectral displacement and the floor displacement response spectrum as a whole can be obtained and peak floor displacement, the floor displacement response spectrum can be approximately “constructed”.

Step 4: Prediction of Inelastic Storey Drift.

It is proposed that the substitute structure method presented in [Shibata & Sozen 1976; Priestley 1995]can be employed for the prediction. Thus, the predicted floor motion (where plastic hinge forms) is treated as the applied ground motion. Further, the upper part of the bifurcated structure is modelled as a substitute structure.

CONCLUSION

1. A two-degree-of-freedom lumped mass model (comprising a "lower" lumped mass and a "upper" lumped mass with a plastic hinge to form above the lower mass has been used to model the multi-storey buildings with a weak storey at upper level.

2. The displacement of the lower lumped mass decreases while the strength reduction factor of the plastic hinge (defining the yield strength of the plastic hinge) increases. Thus, it is conservative to predict the motion of the lower lumped mass based on elastic modal analyses.[section 2]

3. A "floor" displacement response spectrum has been developed based on the motion of the lower lumped mass to study the frequency contents of the motion of the lower lumped mass. The dominant periods of the "floor" displacement response spectrum slightly increase following the formation of the plastic hinge. [section 2]

4. The concept of the substitute structure is employed to predict the inelastic drift behaviour of the upper lumped mass using the “floor” displacement response spectrum. [section 3]

5. A simplified procedure to predict storey drifts in multi-storey building has been conceived incorporating with the concept of substitute structure. [section 4]

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